Radar Detection and Monitoring of Gas Pipeline Leaks

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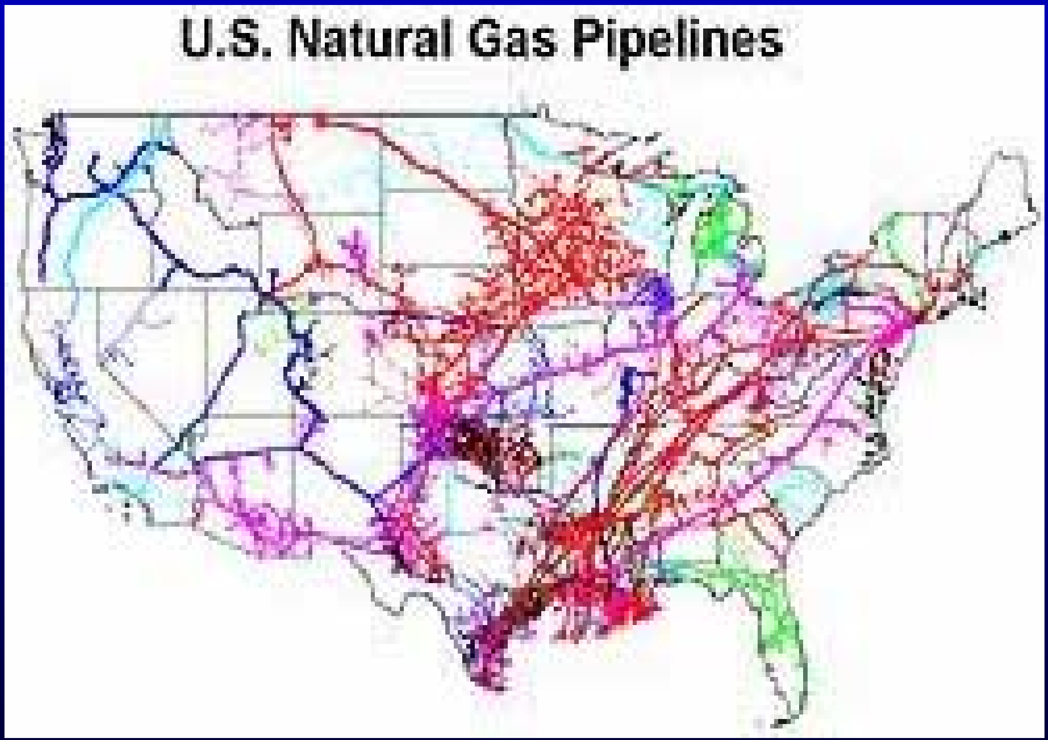
Objective

- To develop a microwave radar sensing and imaging system that can detect and locate gas leaks in natural gas pipelines
  - Perform modeling of leak plumes and estimate their radar cross sections
  - Build hardware and determine detection sensitivity to leaks and detection range

Natural Gas Infrastructure



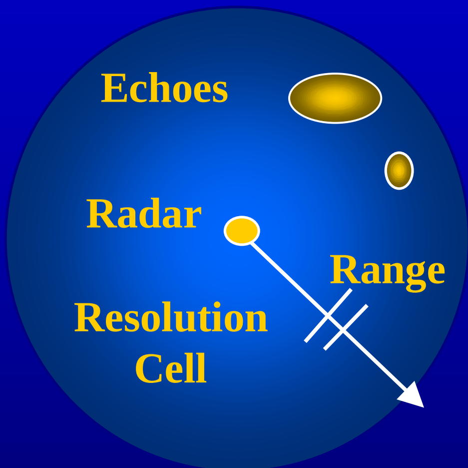
- The U.S. natural gas infrastructure is large and extensive
- Over 2 million miles of transmission and distribution pipelines run from bore wells to homes and industries
- Most of the existing infrastructure is old and aging, raising a great concern for long-term gas reliability and infrastructure integrity
- Remote sensing techniques are needed to detect and locate leaks

Background

- The radar leak detection method is similar in many ways to radar weather prediction
- The source of radar return is the index of refraction inhomogeneities introduced by the flow of methane
- Microwave imaging radars have been used in the past for locating underground oil and gas deposits based on the dielectric contrast of hydrocarbon gases
- We are collaborating with the AOZT Finn-Trade team, St. Petersburg, Russia, who has pioneered this technology for chemical and nuclear detection

Radar Deployment Scenario

Basis of Radar Measurements



Range: R = c t / 2

In-range resolution: $\Delta R = c\ \tau / 2$

Cross-range resolution: $\Delta W = R\ \theta$

where c = velocity of light,

t = roundtrip time,

τ = pulse width, and

θ = antenna beam width

Radar Return Signal

$$P_r = \frac{P_t\ G^2\ \lambda^2\ \sigma}{(4\pi)^3\ R^4}$$

where

P_r = received power,

P_t = transmitted power,

G = gain of the antenna,

λ = wavelength,

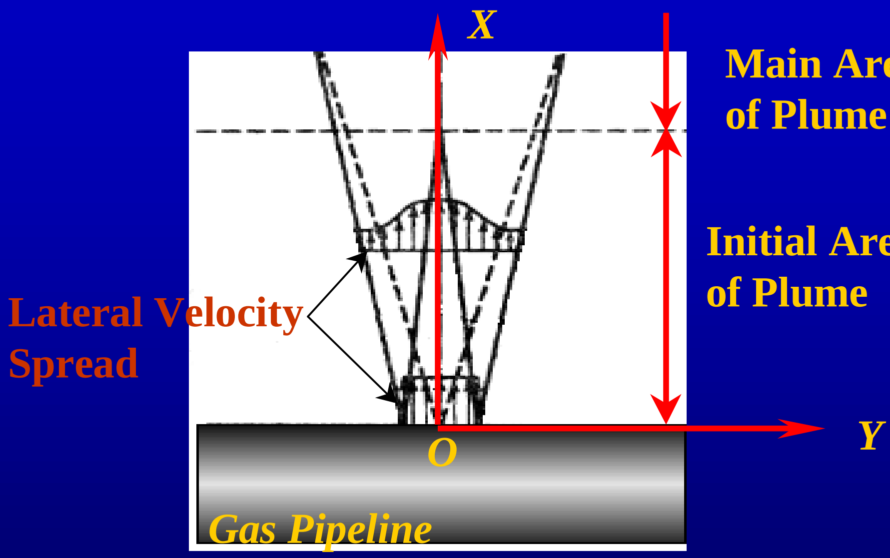
σ = radar cross section of the target

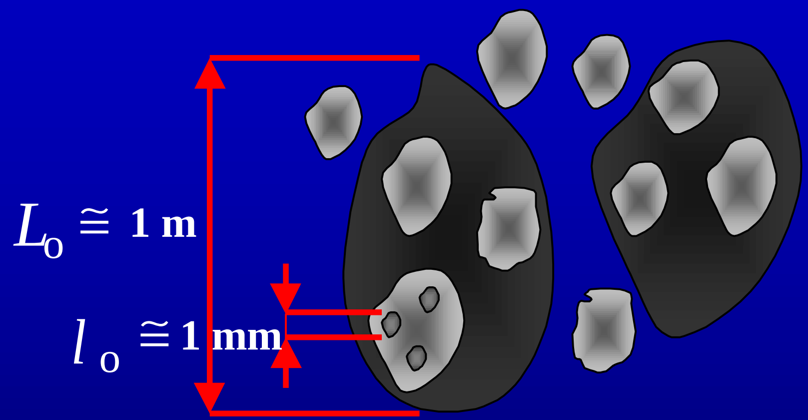
R = distance to the target.

Modeling Approach

- Model the plume spread and gas dynamics for a small hole in a pressurized gas pipe
  - Pipe pressure = 50 kg/cm^2; 1 atm = 1 kg/cm^2
  - Three hole sizes: 5.4 mm, 17 mm, and 54 mm
- Estimate the radar cross section based on index of refraction changes of methane-air mixture

Gas Plume Diagram

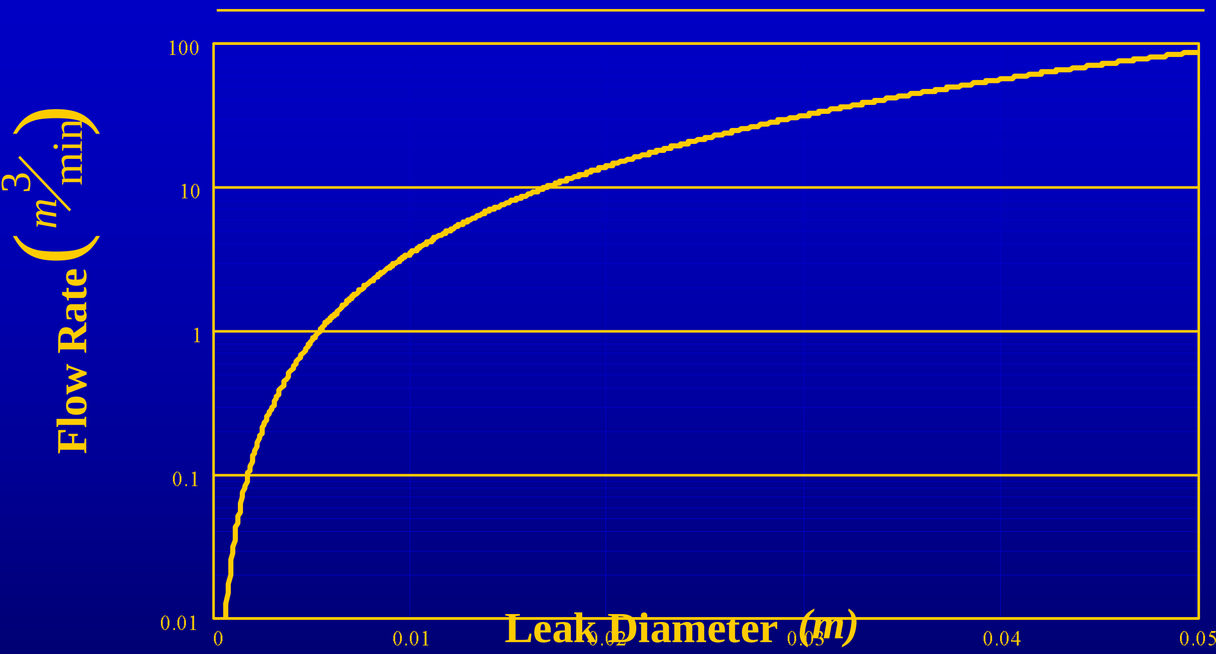




The turbulent vortices: External and the internal scales are shown

- The leak gas velocity depends on the pressure differential between that of the pipe and the atmosphere
- Gas flow from a small hole in a pipe is turbulent in nature, characterized by vortices size 1 mm to 1 m
- Methane density is less than that of the air, hence, the leak creates a force of positive buoyancy

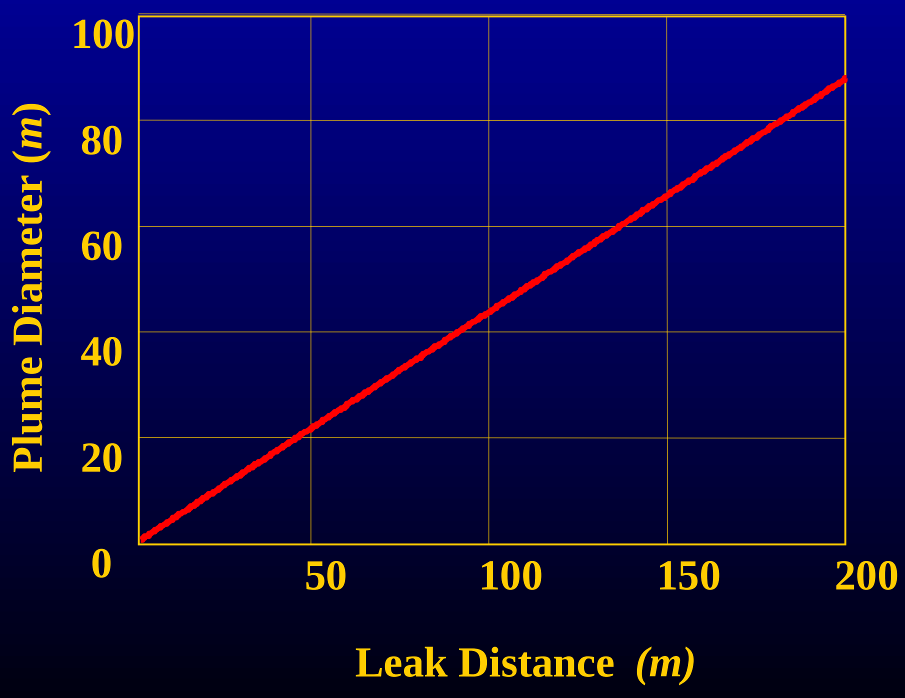
Leak Flow Rate vs. Leak Diameter

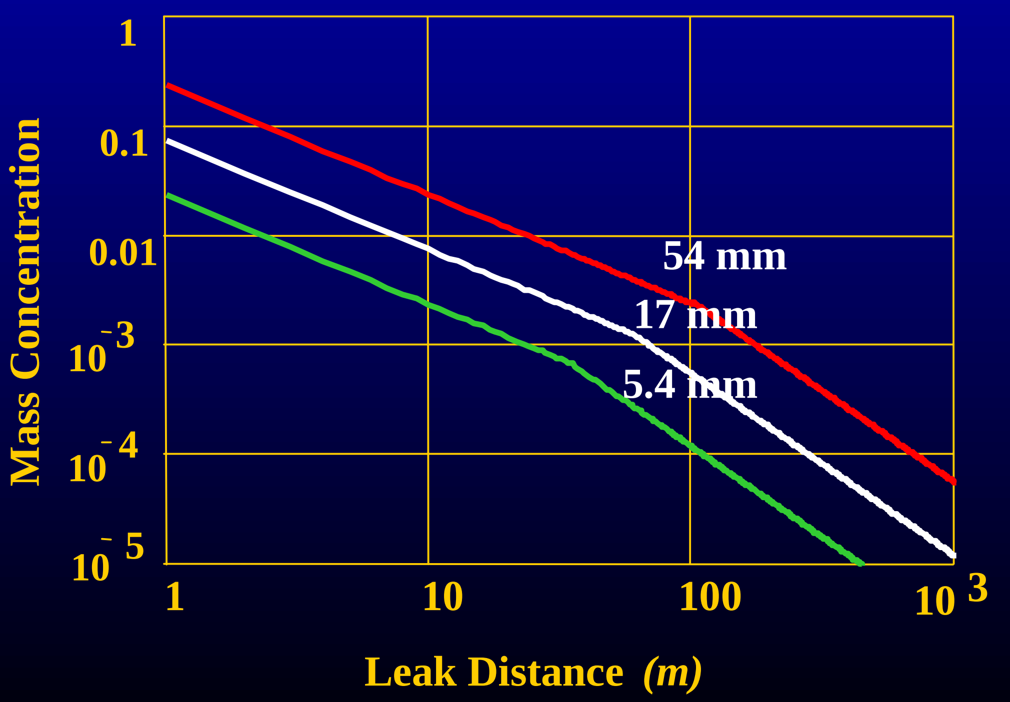


No.	Leak Class	Methane Flow Rate (m^3/min)	Hole Diameter (mm)
1.	Very Small	< 1	< 5.4
2.	Small	1 to 10	5.4 to 17
3.	Medium	10 to 100	17 to 54
4.	Large	> 100	> 54

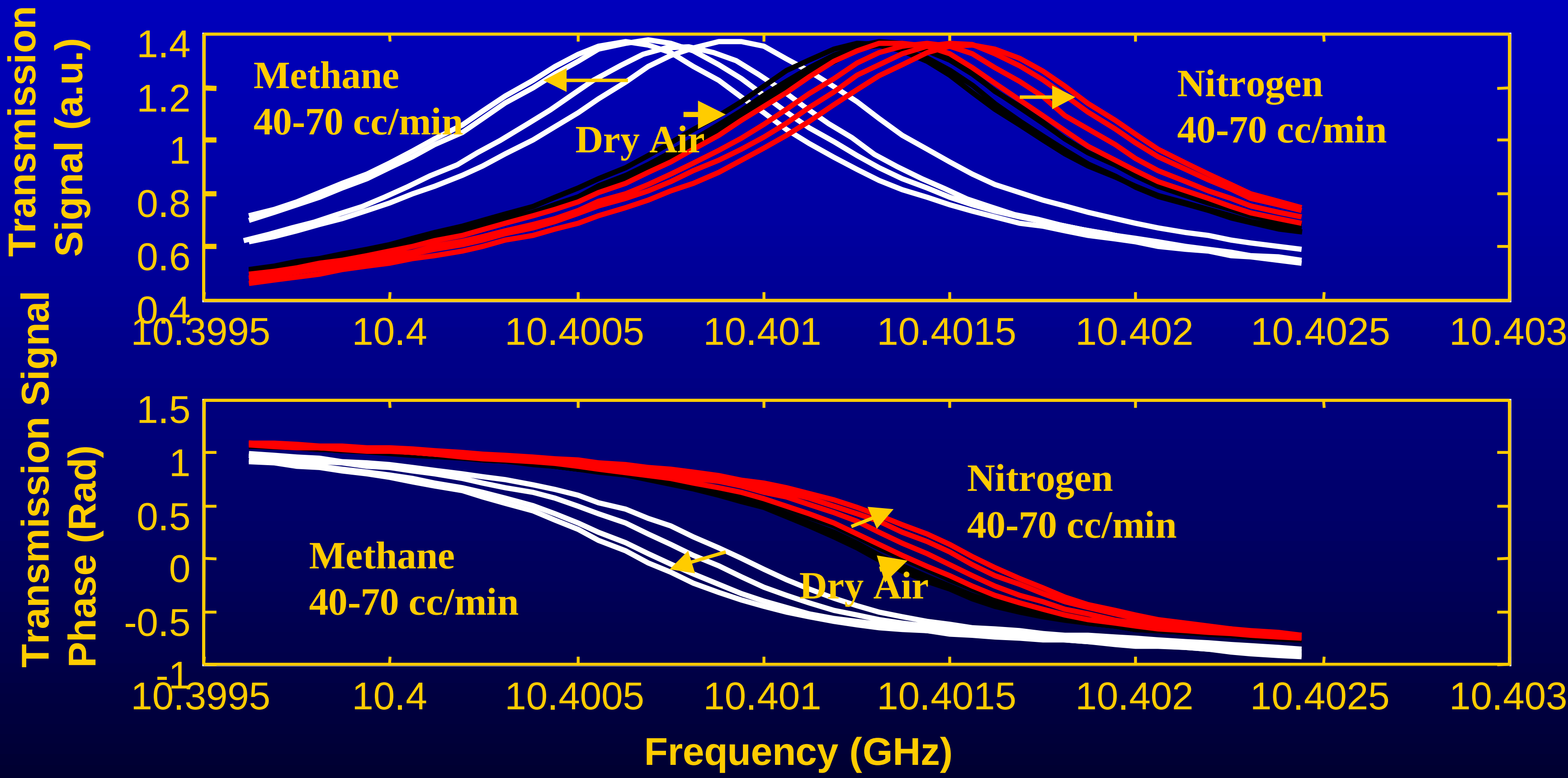
Plume Diameter and Mass Concentration vs. Leak Distance

- Three zones of flow velocities: inertial, intermediate, and buoyancy dominated.



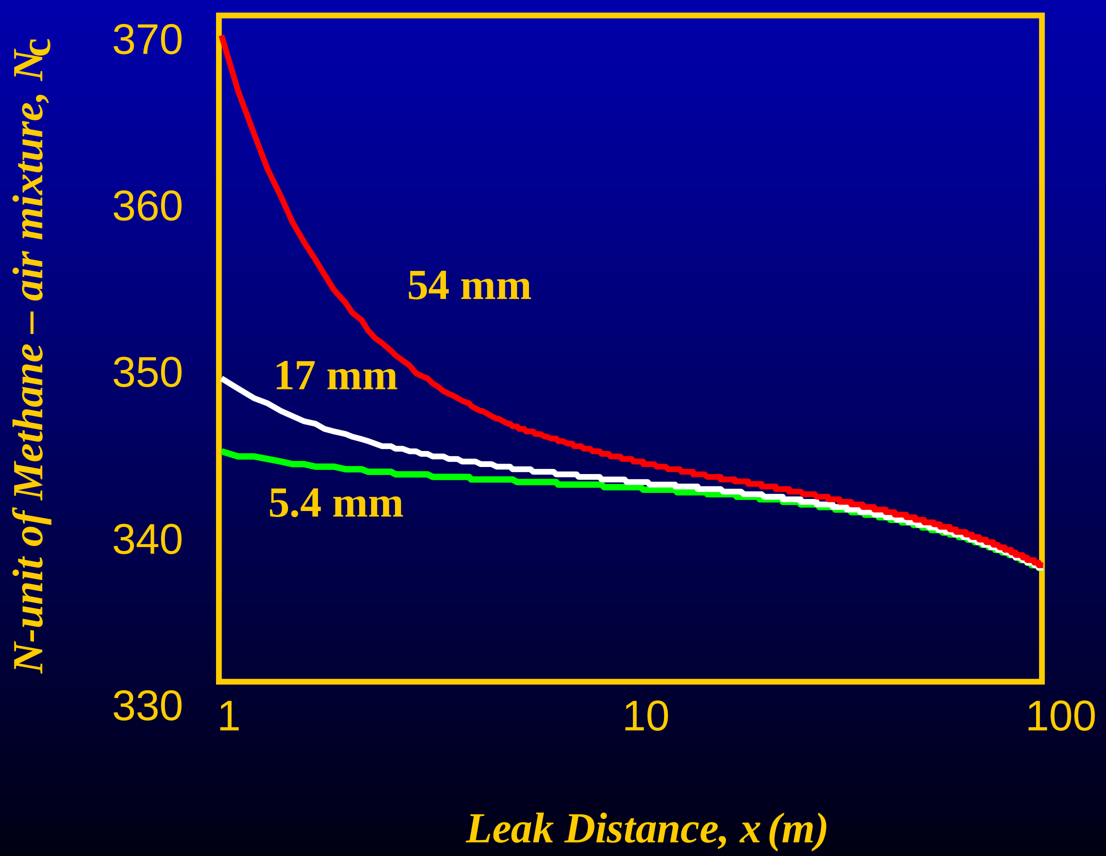


Microwave Cavity Measurement of Permittivity



The measured value of the permittivity for Methane is 1.000670844 and Dry Air is 1.000572890 at 50 cc/min

Index of Refraction of Methane Plume vs. Leak Distance



$N_c = N_{ab}\,(1 - s_m) + N_m\,s_m$

where

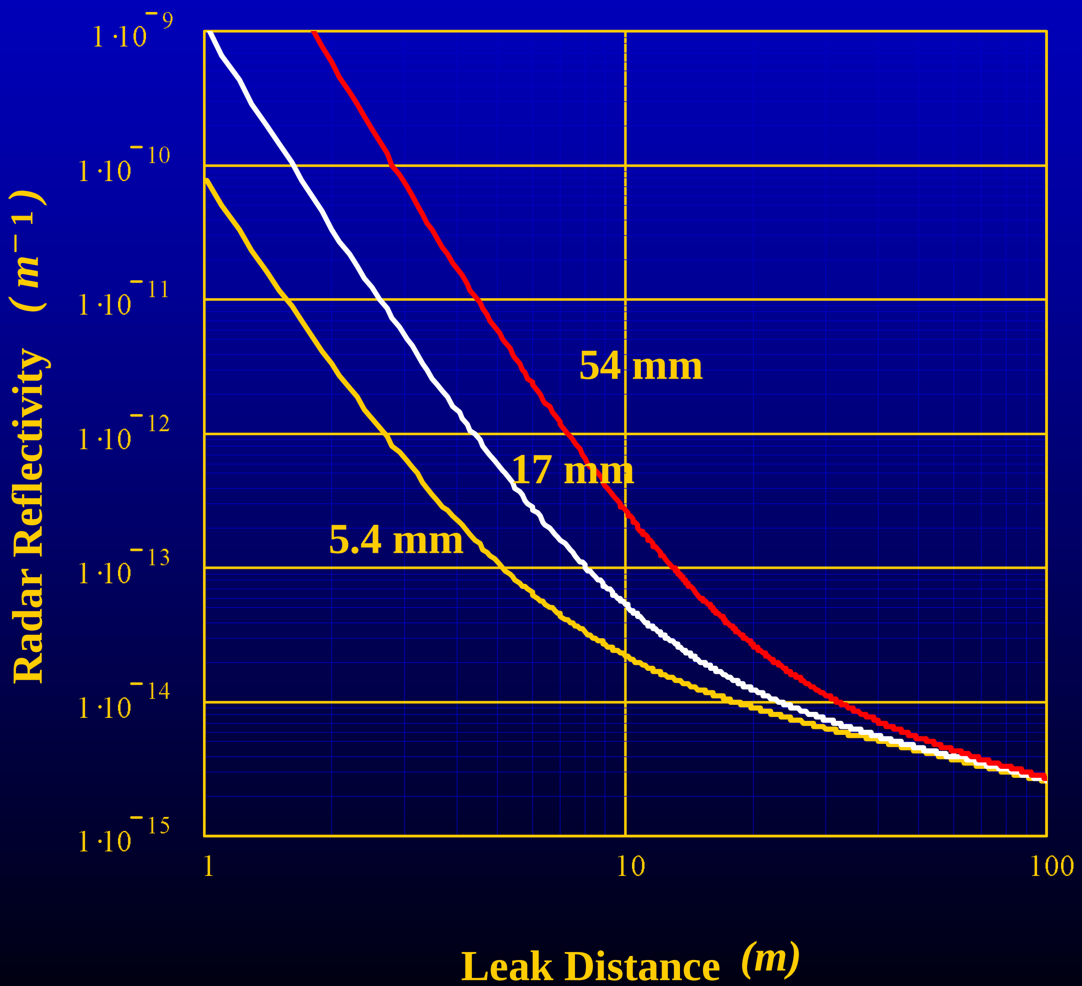
$N_c = (n_c - 1)10^6$

n_{ab}, n_m, n_c = *Index of refraction of air, methane, and mixture, respectively*

n_c = *Index of refraction of methane-air mixture*

s_m = *methane concentration*

Radar Reflectivity vs. Leak Distance



$\sigma_0 = 0.38\, C_n^2(x)/\lambda^{0.33}$

where σ_0 = *radar reflectivity* m^2/m^3

λ = *wavelength in m*

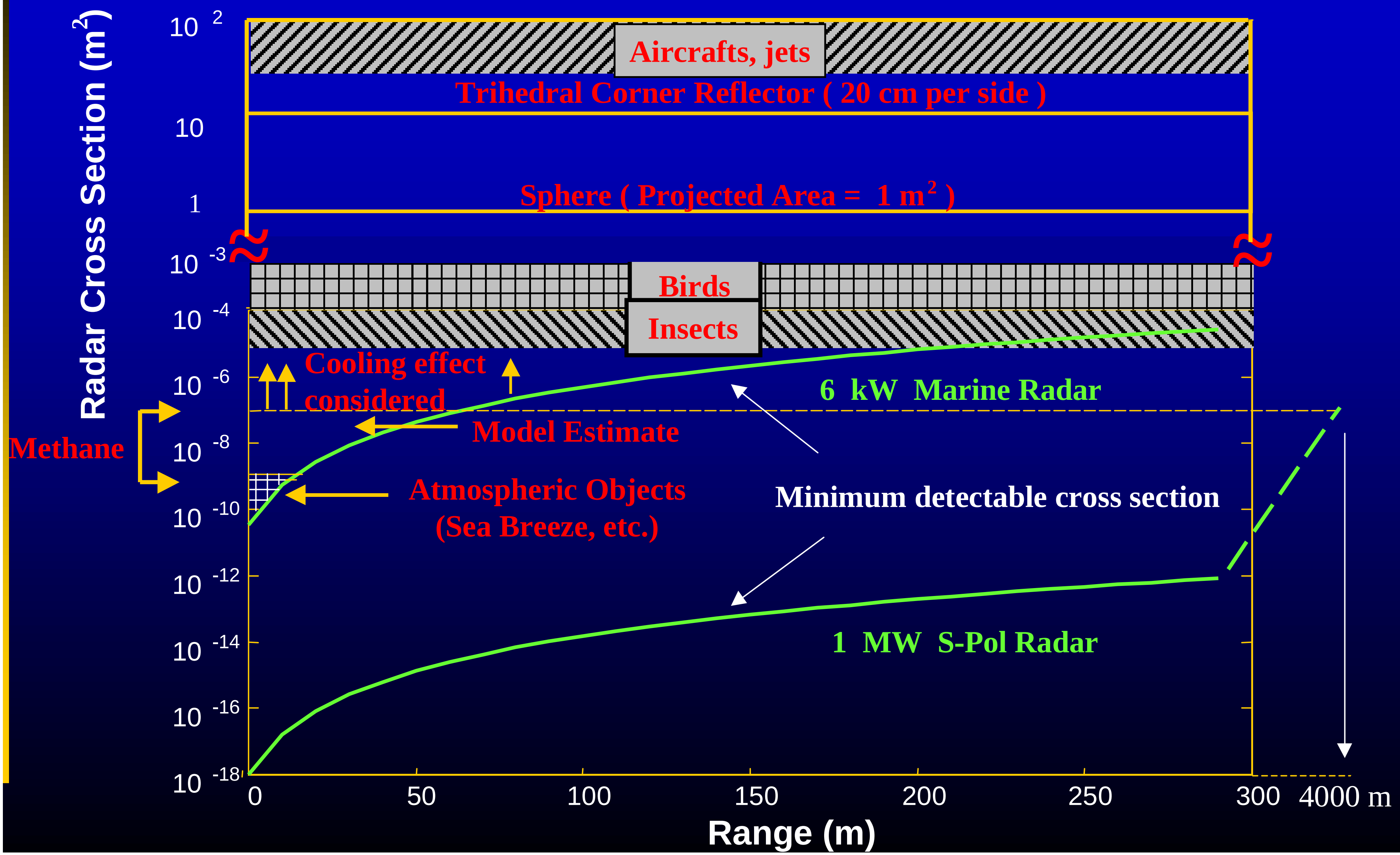
C_n^2 = *Structural constant, a measure of the mean-square of the fluctuations in the refractive index of the turbulent medium*

$\sigma = \int \sigma_0 V_\tau dV_\tau$

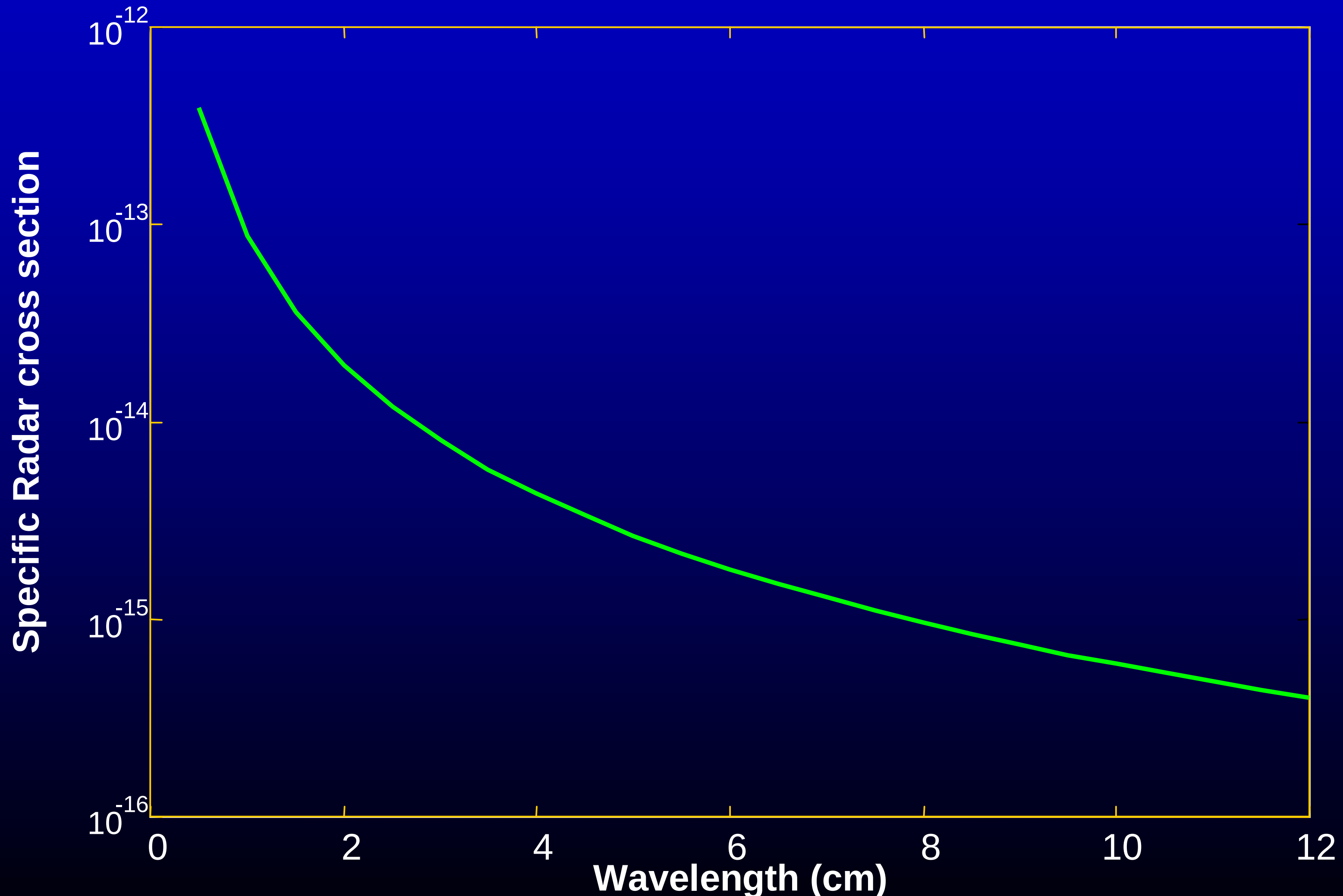
where σ *is the radar cross section* (m^2)

V_τ = *resolution volume element*

Radar Cross Section of Methane vs. Other Targets



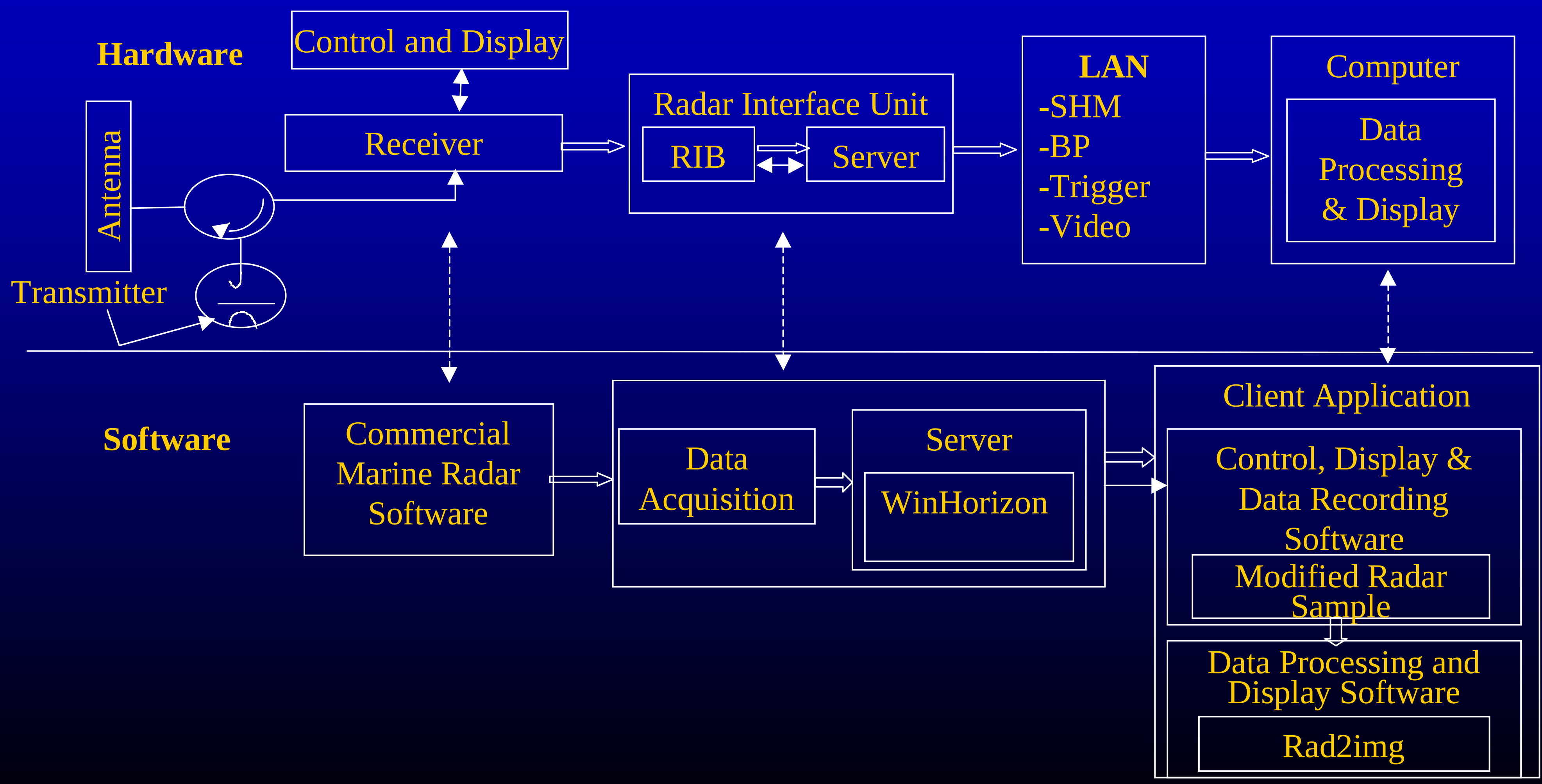
Plume Cross Section with Wavelength



Radar Setup

- X band, 6 kW, 80 ns pulsed radar
- Slotted waveguide array antenna
- Resolution at 60 m: In-range=12 m
  Cross range= 1.98 m x 23.0 m

Schematic of Radar Data Collection



Correspondence Between Radar Screen Image and Acquired Image

Screen Image

Acquired Image

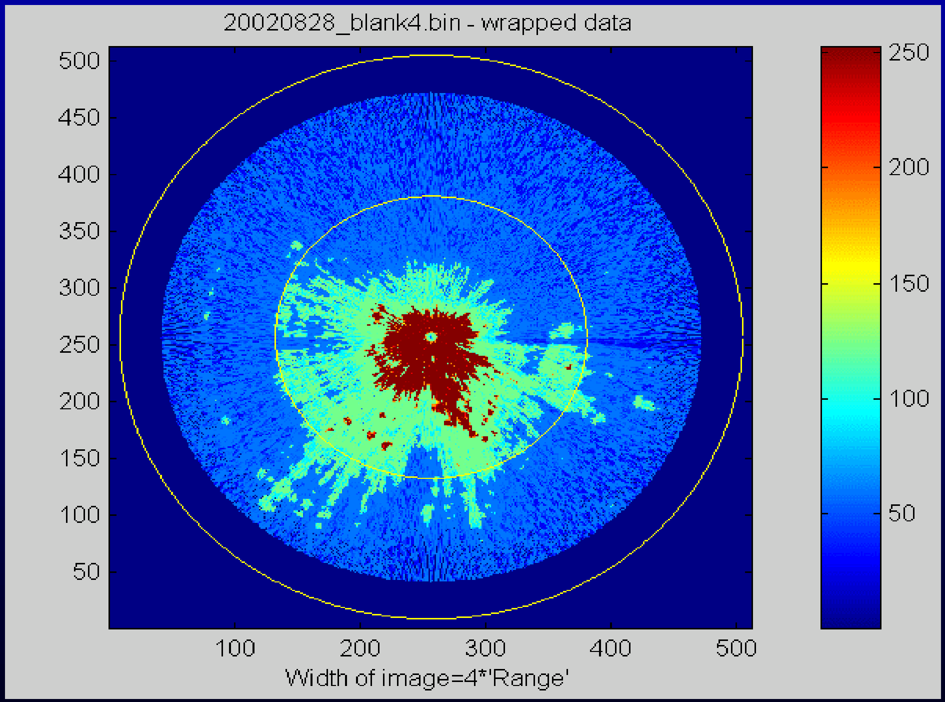
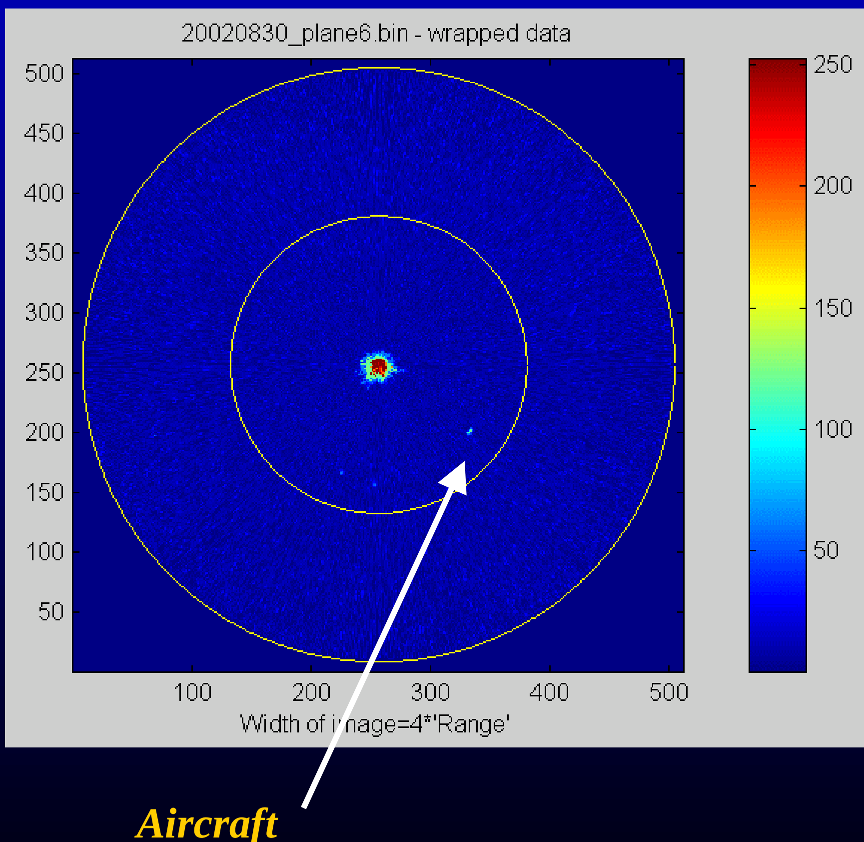
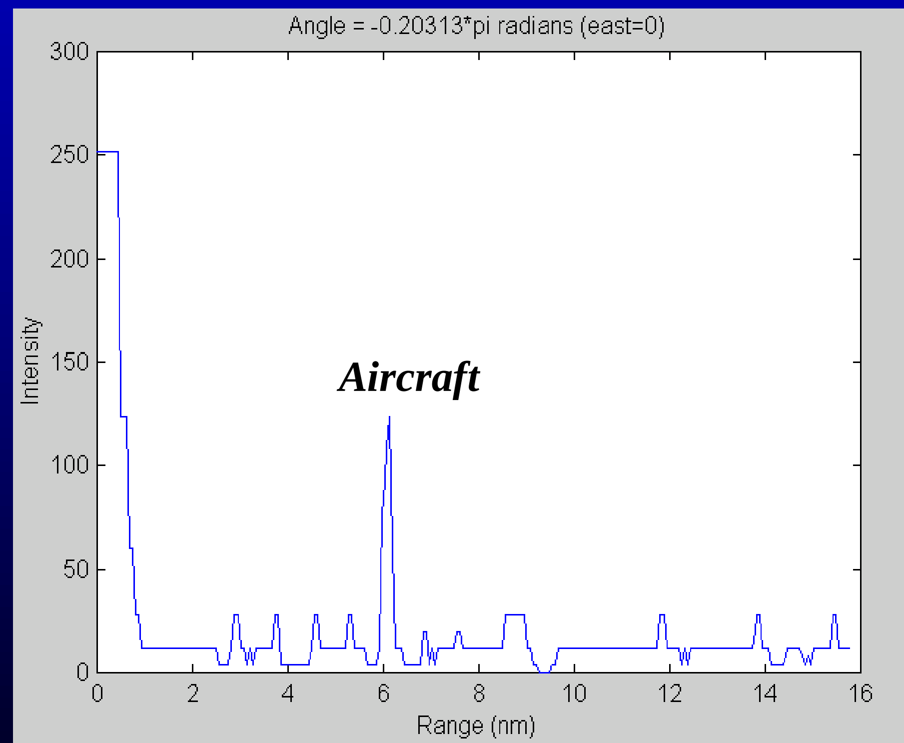
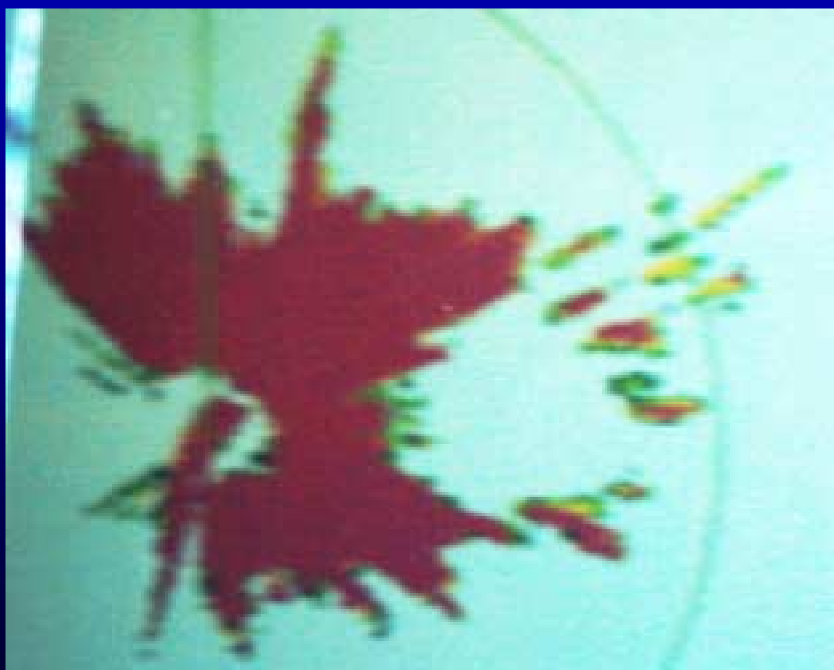


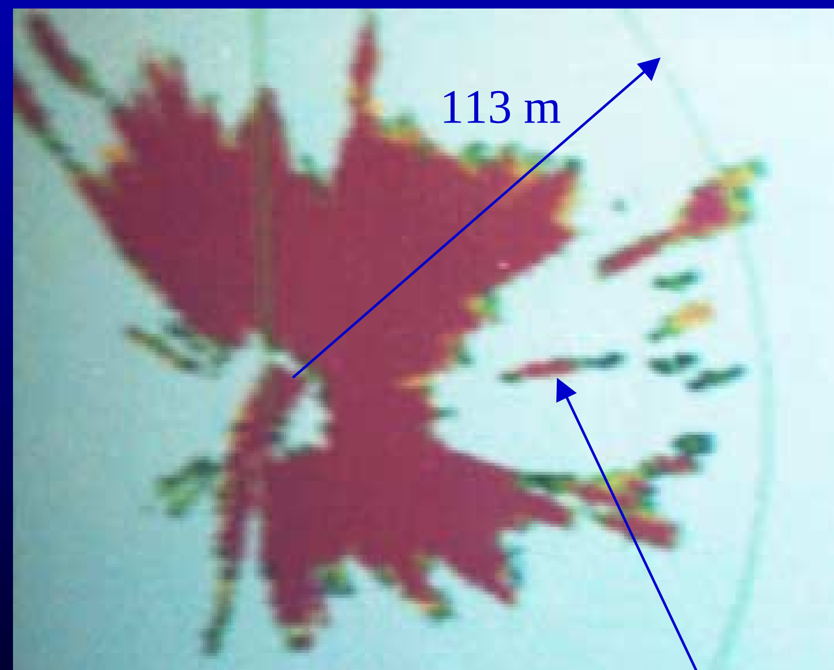
Image of an Aircraft and Corresponding Signal Trace





Calibration with a Corner Cube





Corner cube (20 cm/side)
60 m away

Accomplishments

- Completed modeling of the radar cross-section of leak plumes
- Installed a marine radar and tested its capability to detect short-range targets against ground clutter
- Completed computer interfacing of the radar for data collection and signal processing
- Calibrated the radar with a corner cube (reflector) at a distance of 60 m

<u>Deliverables Completed</u>

- State of the art survey of remote leak detection
- Radar cross-section modeling report

<u>Publication</u>

N.Gopalsami, D.B.Kanareykin (AOZT Finn-Trade), V.D. Asanov (AOZT Finn-Trade), S. Bakhtiari, and A.C.Raptis, "Microwave Radar Detection of Gas Pipeline Leaks," Paper presented at the 29th Annual Review of Progress in Quantitative Nondestructive Evaluation (QNDE), Bellingham, WA, July 14-19, 2002.

Accomplishments (Cont.)

Industrial Interactions

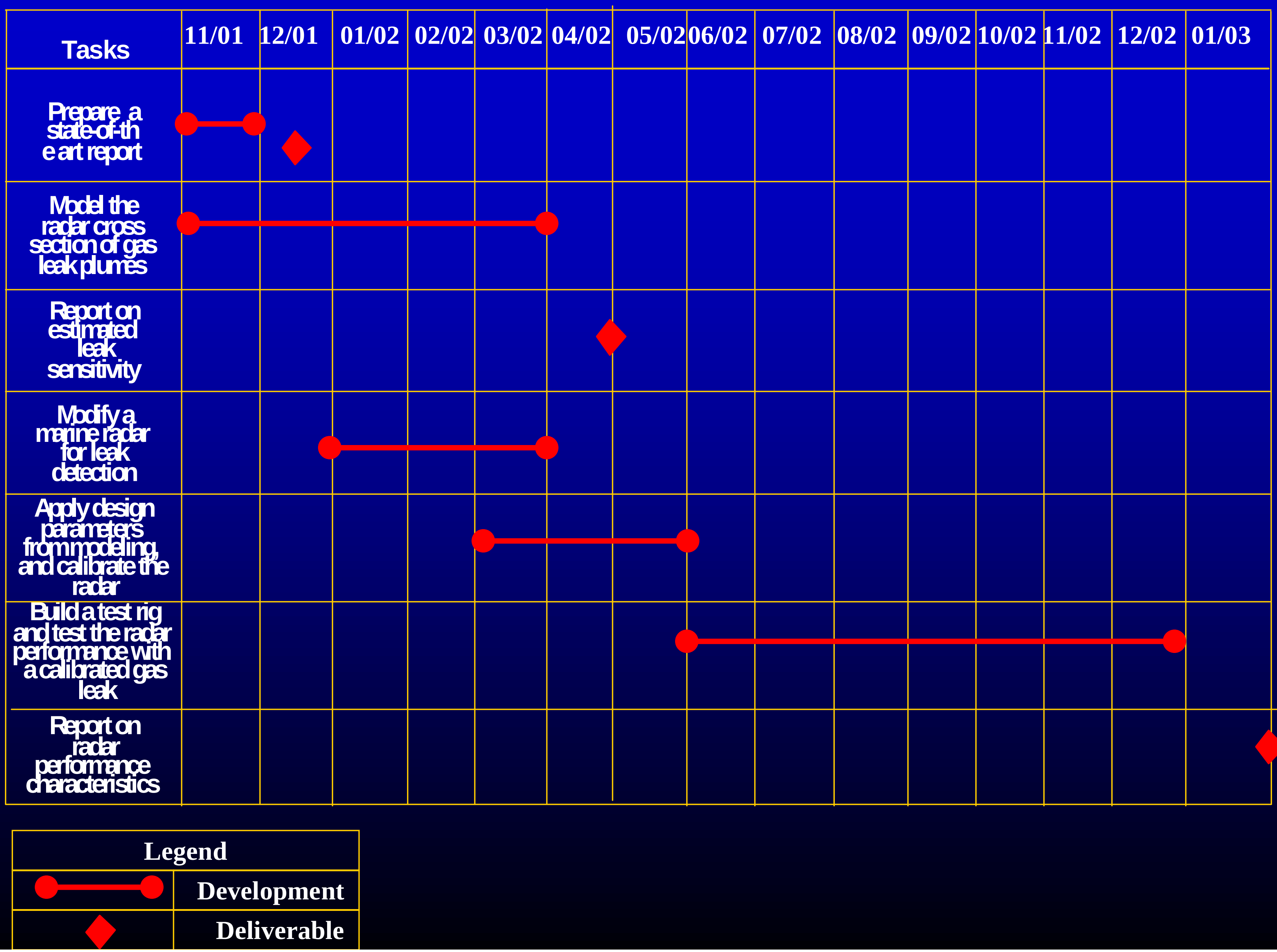
- BP Amoco
  - Met on 8/15/02; Keen interest for leak imaging; Next meeting 9/24/02
- Univ. of Alaska/Alaska Pipelines
  - Interested in leak detection; Made an invited presentation on 8/22/02
- IGT
  - Responded to inquiries
- TCS, Indian company
  - Interested in remote sensing

Conclusions

- We have developed a gas-dynamic model that predicts the extent of methane plume dispersion and concentration in the atmosphere for a given leak from a gas main
- The sources of enhanced radar return of the methane leak are the turbulent inhomogeneities of the leak jet, a decrease of gas temperature with attendant water vapor condensation, and the index of refraction change of the methane-air mixture
- The radar cross section was calculated based on a scattering model of fluctuations of the refractive index of turbulent medium
- Modeling results show feasibility of methane leak detection with special purpose radars

Future Work

- Team up with an industry partner for further development and commercialization
- Set up controlled (calibrated) leaks of methane gas
- Test the radar performance for detection of the methane leaks
- Develop appropriate signal and image processing to improve leak detection sensitivity
- Investigate below-ground leak detection capability of the radar
- Develop a radar design for a flyby system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Prepare a state-of-the art report
Model the radar cross section of gas leak plumes
Report on estimated leak sensitivity
Modify a marine radar for leak detection
Apply design parameters from modeling, and calibrate the radar
Build a test rig and test the radar performance with a calibrated gas leak
Report on radar performance characteristics
Legend
Development
Deliverable